# Time-Frequency Analysis of Upper Limb Motion Based on Inertial Sensors

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***Abstract*—In recent years, inertial sensors have been broadly used in 3D human motion monitoring as an affordable solution. The time domain parameters e.g. kinematic parameters and kinetic parameters have already been widely studied. 3D orientation and position measurement are the most common used kinematic measurements for motion monitoring. This paper focuses on the frequency domain analysis and time-frequency analysis by using inertial sensing sensors. The inertial sensor was first validated for its ability in frequency detection by using a vibration generator. Then experimental tests were conducted on a healthy volunteer for a range of upper limb motion tests including Nine-hole peg test (NHPT) and drawing test. The results showed that additional information can be provided by using the time-frequency analysis, which can potentially provide insights on human upper limb movement.**

***Keywords—time-frequency analysis, upper limb, motion monitoring, NHPT***

## I. INTRODUCTION

Human upper limb monitoring is of great importance in the assessment of upper limb impairment of patients with neurological conditions [1]. Upper limb rehabilitation which consists of different interventions is used to help these patients restore the motor function of their upper limbs [2]. In order to assess the recovery of patients' upper limb motion throughout the rehabilitation, different clinical assessment scales including Fugl-Meyer [3], Motor Assessment Scale [4], Modified Ashworth Scale [5] have commonly been adopted in the clinical settings. However, these clinical scales are very subjective and sometimes not reliable [6].

With the emerging of different sensing systems e.g. camera based systems [7], inertial sensing systems [8], electromyographic (EMG) systems [9] have been used to provide objective measurements of upper limb movement. Time domain parameters for both kinematic and kinetic measurements have been analysed. Kinematic measurements which are used to describe the movement including time, linear acceleration, linear velocity, and linear position for different upper limb segments and joints [10]–[12]. These analyses of the variables were analysed to show how this data can increase the depth of information available to describe the upper limb motion and what additional information they can provide to the clinicians [12], [13]. Kinetic analyses of human movement includes torque, inertia, and angular velocity [14].

Application of inertial sensors shows some good correlation to clinical scales and also is able to provide additional insights during rehabilitation [15]. Also low cost sensors e.g. gaming sensors are proved valuable tools for the measurement of upper limb recovery in clinical trials [12], [16]. Power spectrum distribution patterns have been previously studied by researchers in the evaluation of EMG signals in upper limb disability of stroke patients [17]. Moreover, the features extracted from different frequency band have been used to decode different limb movements [18]. The frequency domain analysis and time frequency analysis on the inertial sensing units e.g. accelerometer will be able to provide additional information especially in analysing the neurological conditions which have tremor as the presenting feature. Therefore, this paper aims to conduct the frequency domain analysis and time-frequency analysis for evaluating and quantifying the upper limb performance. The data analysis methods include frequency domain analysis, and time-frequency domain analysis will be discussed. It is hoped that more quantitative data analyses will provide objective and additional information on upper limb movement which will be of value to the clinician in monitoring response to rehabilitation and assessing the efficacy of the rehabilitation programs.

## II. METHODS

In this section, the frequency analysis and time-frequency analysis will be mainly discussed. The frequency analysis of the upper limb linear acceleration is presented as it is thought to be useful in identifying the presence of tremor and how that tremor responds to treatment. Also, time-frequency analysis will be used to discover the pattern of frequency changes for the movement over a period of time. It can be very useful to understand distinctive patterns for different upper limb motion tests.

### *A. Frequency domain analysis*

Pathological tremor [19] can be correlated to specific diagnosis of some conditions such as Parkinson's disease and essential tremor, and is also useful in the assessment of the rehabilitation process. In the measurements made in this work, tremor usually most obviously presents itself in the acceleration data and also the accelerometer is sensitive in picking up the small movement. Analysis of the acceleration frequency spectrum should provide objective information on the amplitude and frequency content of the tremor. In the frequency analysis, the Fast Fourier Transform (FFT) [20] has been used. Moreover, as the presence of low level tremors, which are difficult to detect using conventional screening, can precede the normal diagnosis of these conditions (e.g. Parkinson's disease and essential tremor) by several years [21], this analysis may prove to be a useful diagnostic tool.

### *B. Time-frequency analysis - the Spectrogram*

The presentation of the frequency spectrum [22] may be able to provide additional movement information compared with time domain analysis. The spectrogram is used here as a way to present how the frequency content changes over time. It can provide both frequency response and time in one plot. Usually, in a spectrogram plot, the x-axis (horizontal axis) represents time, and the y-axis (vertical axis) represents frequency. The amplitude of each frequency component is represented by colour.

## III. Experiment

### A. *Validation of the frequency test of an inertial sensor – experiment set-up*

The sensor frequency test set-up is shown in Fig. 1. This utilises a vibration generator and a function generator together to generate a known vibration frequency (e.g. 15Hz or 20Hz) whose 3D linear acceleration output, frequency spectrum and spectrogram has been presented in Fig. 6 (a) (b) (c) on all three axes.

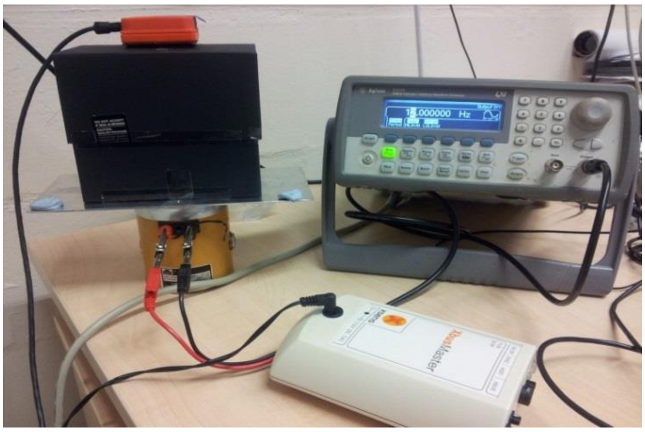


Fig. 1. Sensor frequency test set-up

### B. *Different upper limb motion tests on a healthy volunteer*

An initial evaluation of this technique on a healthy volunteer was carried out as follows. Four sensors were aligned on the upper arm and lower arm respectively as seen in Fig. 2. The volunteer stretched the arm out in front and kept the arm still and parallel with the horizontal plane. The inertial sensors were used to capture the involuntary tremor.

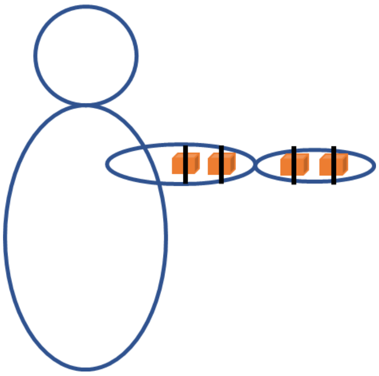


Fig. 2. Involuntary tremor test

### C. *Nine-hole peg test (NHPT)*

The nine-hole peg test [23] is a test to assess fine motor control and coordination (finger dexterity). The nine-hole peg test board is shown in Fig. 3. The subject is asked to pick up the pegs one at a time from the container and insert them into the nine holes. Normally the subject is asked to use his or her preferred way to complete the task. During the test, the therapist uses a stopwatch to measure the time taken to carry out the test. Time and whether the task is completed will be part of the score. The typical completion time for healthy adults is about 20 seconds [23].

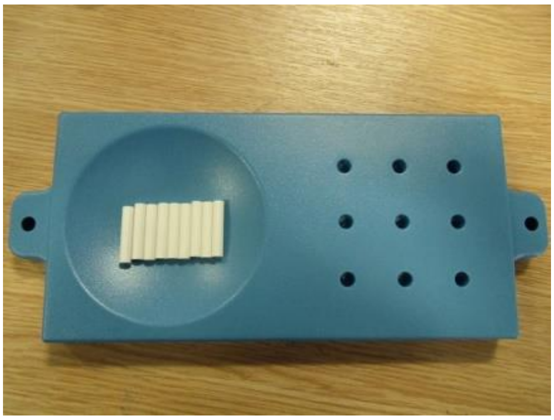


Fig. 3. Nine-hole peg test board

### D. *Drawing test*

In the drawing test, the subject is asked to copy over a circle, square and triangle drawn on the test paper [24] as shown in Fig. 4. This test is believed to provide useful information about the range of joint motion and coupling between the shoulder and elbow joint and also fine motor control of wrist and fingers [25]. In this example the position of the wrist throughout the drawing process is tracked. It should be noted that the sensors are able to track the gross movement of the hand and other joints on the upper limb, not the finger movement.

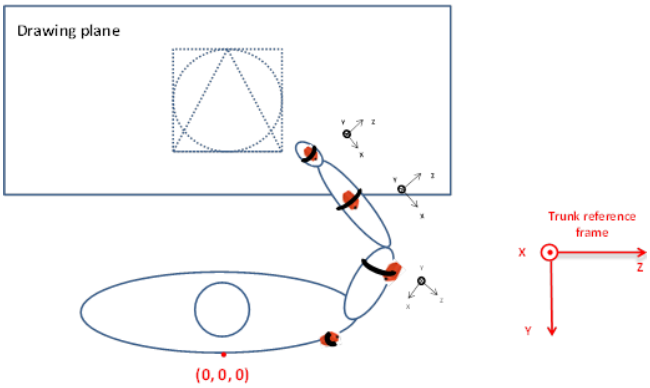


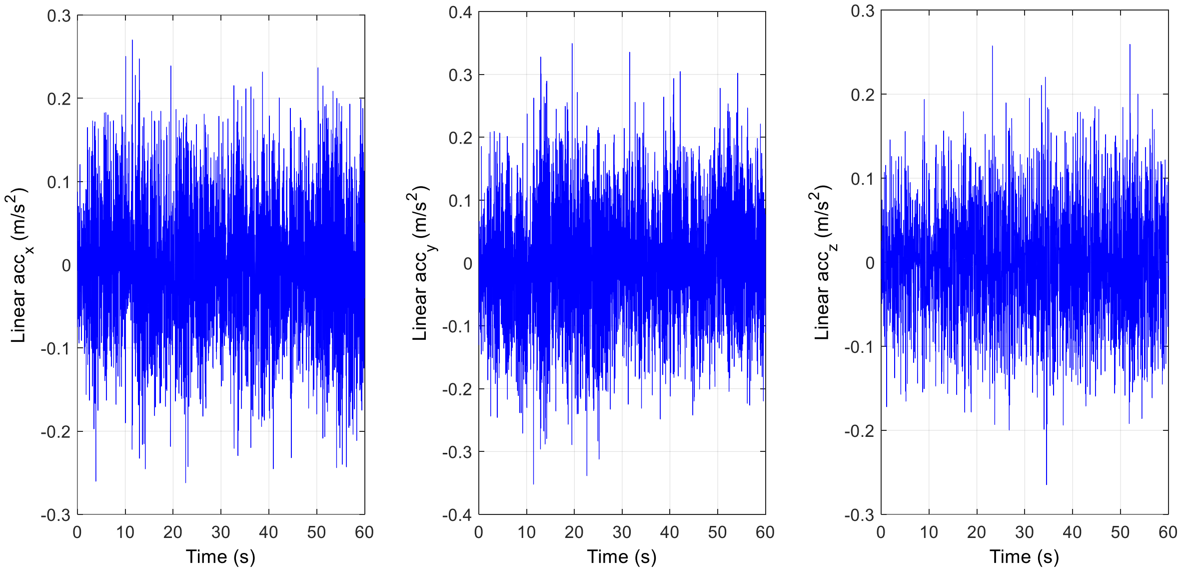

Fig. 4. Drawing test

## IV. Results

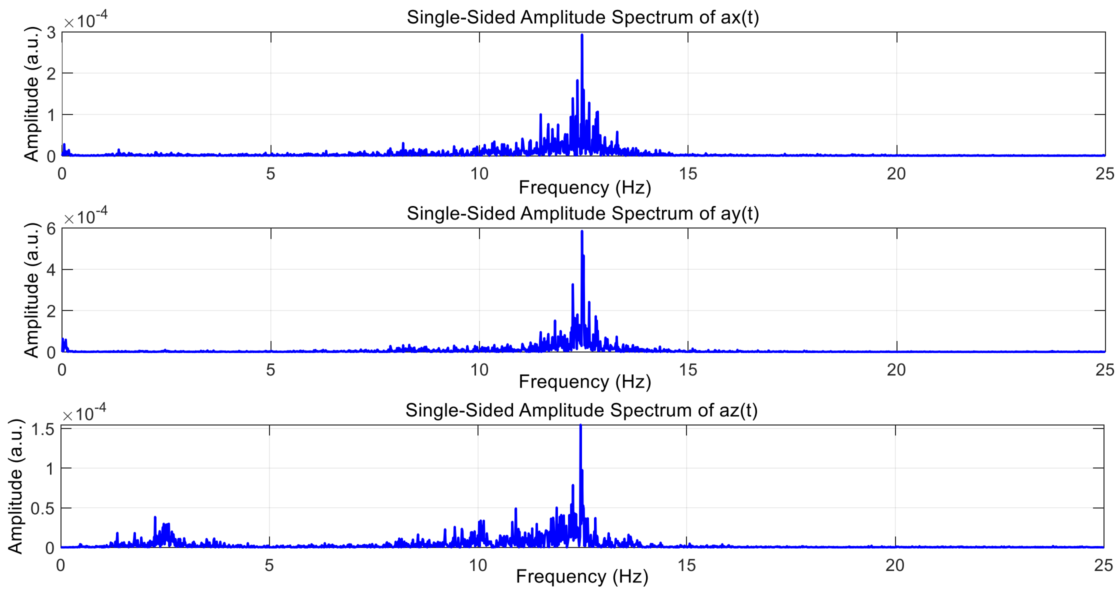
### A. *Frequency analysis results*

Fig. 5 (a) shows 3D linear acceleration (gravity component has been removed) of the sensor on the forearm in the global reference frame. Usually the frequency analysis is done on the linear acceleration. Fig. 5 (b) shows the frequency spectrum of the linear acceleration on all three axes.

From Fig. 5, it can be noted that most of the frequency components occur between 10Hz to 15Hz in the test of the upper limb involuntary movement of the healthy volunteer as trying to keep the stretched arm still as shown in Fig. 2. The magnitude and the frequency of the tremor may be of useful clinical value. But in future study, the evaluation of this analysis will not be carried out on patients especially patients who have tremor, this analysis may be a useful tool in providing quantitative analysis of their tremor.




(a) Linear acceleration data




(b) Frequency spectrum analysis of linear acceleration data

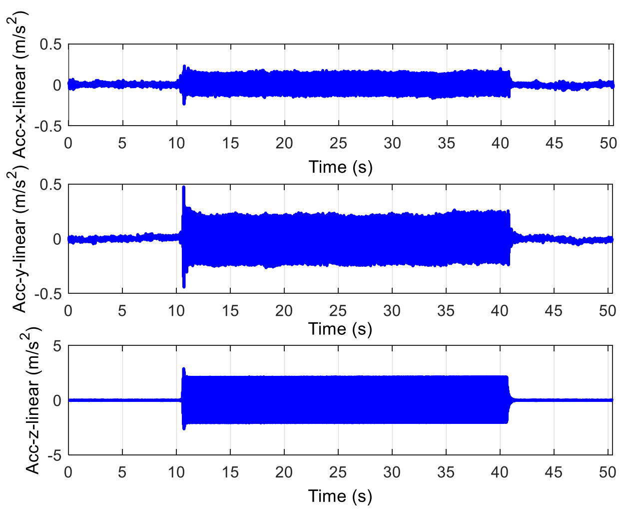
Fig. 5. Frequency analysis of acceleration

## B. *Time-frequency analysis results*

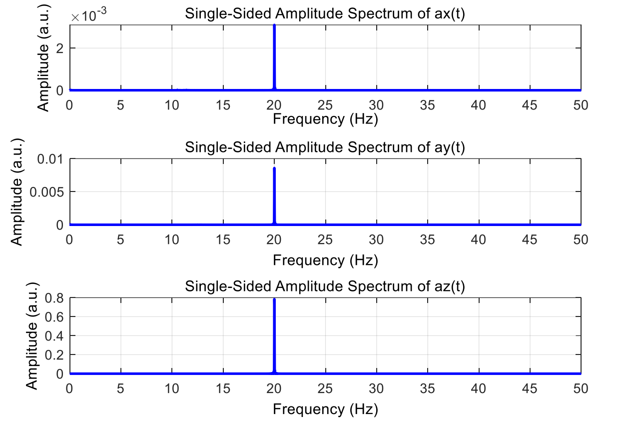
### *1) Validation of frequency of an inertial sensor*

In Fig. 6 (b), it is noted that the scales of the frequency spectrum plots are different on x, y and z axes, where the scales on the x and y axes are much smaller than that of the z axis. It is because the 20Hz vibration movement is mainly applied on the z-axis of the sensor (see Fig. 1). Fig. 6 (c) shows the 20Hz frequency component in the spectrogram. The start and end point of the test can be seen from this plot, which runs from 10 seconds to 40 seconds.

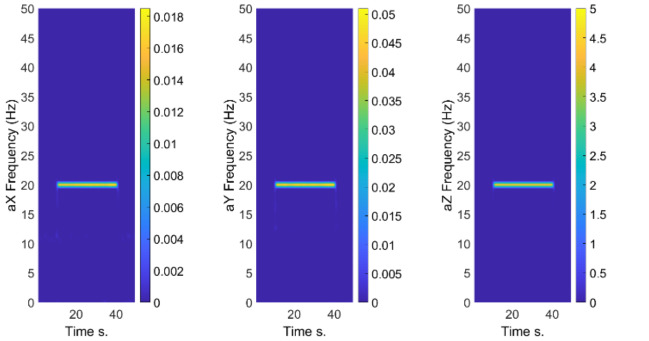
However the test of a single 20Hz frequency component is quite a simple presentation and is relatively easy to interpret. Whether this is the case for more complex movements has to be evaluated. Therefore a number of tests done by a healthy volunteer have been used as examples of a spectrogram for a more complex set of movements. The analyses are presented in the following subsections.



(a) Linear acceleration for a single 20 Hz excitation frequency on all three axes




(b) Frequency spectrum analysis of linear acceleration for a single 20 Hz excitation frequency on all three axes




(c) Spectrogram of a single 20 Hz excitation frequency on all three axes

Fig. 6. Frequency analysis for a single 20 Hz excitation frequency on all three axes

## 2) *Time-frequency analysis of NHPT*

NHPT is one of the tests which has been widely used in the evaluation of upper limb movement. In addition to the NHPT which commonly used clinical assessment tests, there are also other assessments which focus on the functional ability of the patients, for example, drinking water, shaving and combing hair.

The start and end of each of the nine peg movements can be seen from the Fig. 7 since there is nearly no movement during the peg intervals. The colour density represents the frequency amplitude which is thought to be correlated to the energy of the motion. This representation may also provide additional useful information in the clinical assessment of patient recovery. However the patterns are complex and further work will be required to determine the significance and value of this form of data presentation. But this is another advantage of using the inertial measurement system as information that cannot be gained from the traditional methods is now available.

More detailed results are in Fig. 8. It is noted that most of the movement frequencies are below 3Hz. And the spectrogram on the x-axis (Fig. 8 (c)) shows movement energy and frequencies for each peg movement.

## 3) *Time-frequency analysis of drawing test*

In the drawing test, both the designed path for the fingers/pencil and the drawn paths of the hand are presented in Fig. 4. In this experiment, the healthy volunteer was asked to repeatedly drawing four squares in one test.

The start and end of each of square drawn can be seen from the Fig. 9 and it is noted that there is no movement during each of the square drawing intervals. Different frequency pattern can be observed on 3 different axes.

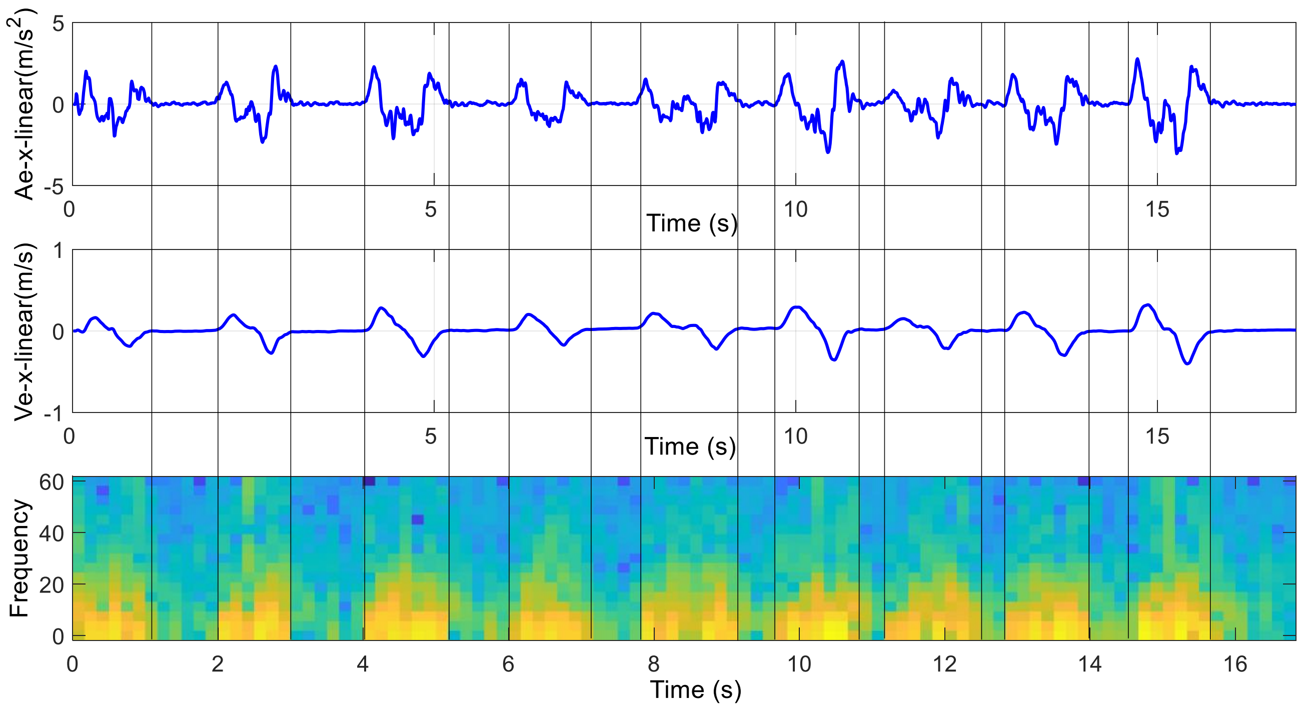
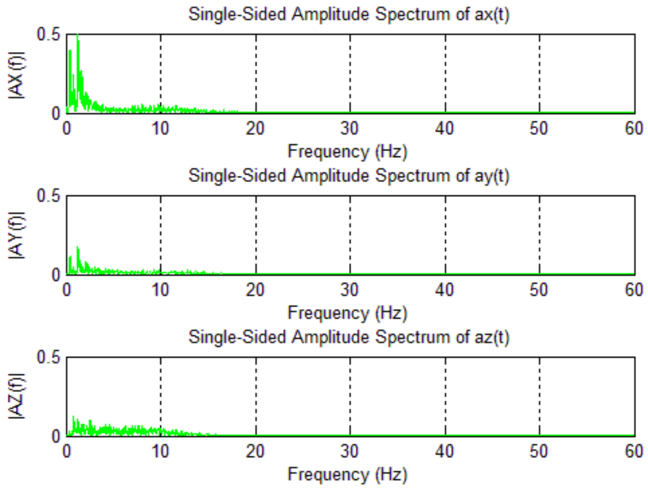
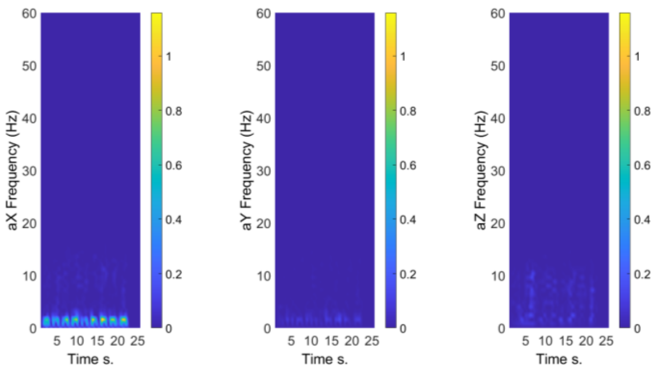


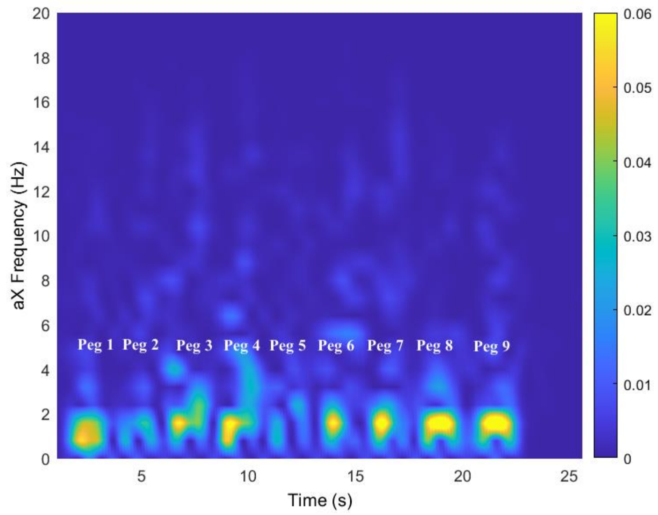

Fig. 7. Analysis for a NHPT




(a) Frequency spectrum analysis of a NHPT on all three axes

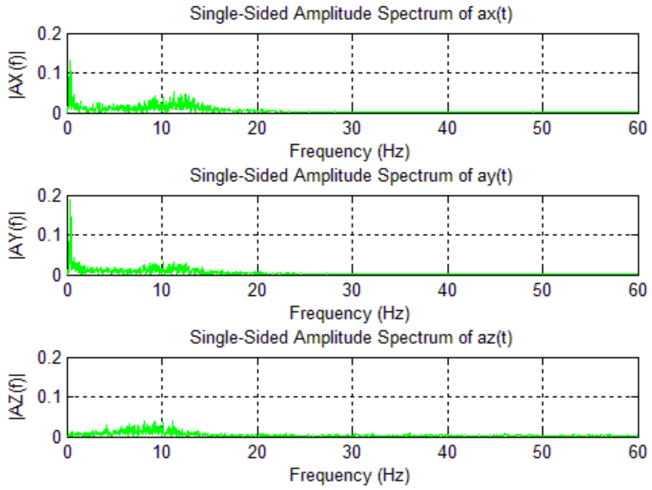



(b) Spectrogram of a NHPT on all three axes

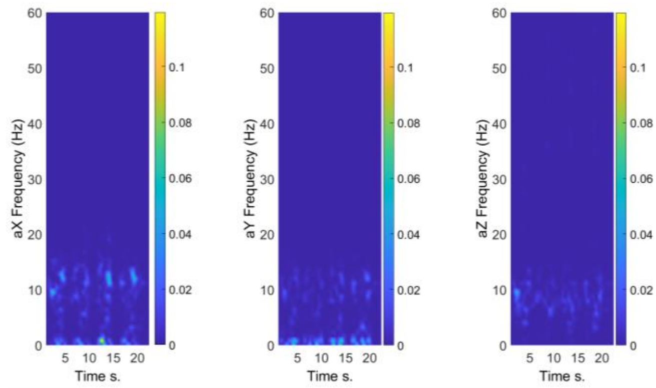



(c) Spectrogram of a NHPT on x-axis only

Fig. 8. Spectrogram of a NHPT




(a) Frequency spectrum analysis of a drawing test on all three axes




(b) Spectrogram of a drawing test on all three axes

Fig. 9. Frequency analysis for a drawing test (4 squares were drawn in this test)

## V. CONCLUSION

In this paper, the spectral measurement of the upper limb motion has been done. The sensor is initially tested by using a vibration generator and the results demonstrate that the sensor is able to accurate measure the frequency. Experiments have also been done for a NHPT and drawing test for a healthy volunteer and the results showed that it is able to capture insightful information from a continuous movement and potentially can be used to analyse the different patterns in NHPT and drawing test. It could potentially work as a useful method and provide additional insights in clinical rehabilitation.

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